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Early Detection of a Solar Flare

A Study of X-Ray, Extreme Ultraviolet, H-Alpha, and Solar Radio Emission From Solar Flares

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Early Detection of a Solar Flare
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R. F. DONNELLY

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ABSTRACT

Solar X-ray, extreme ultraviolet, Hα and radio emission were studied to determine what solar radiation is best suited for an automatic flare alarm system aboard a satellite for the detection of the start of a solar flare. Although hard X-rays ($\lambda \ll 1$ Å), centimeter-wavelength solar radio bursts, and flashes at certain EUV wavelengths usually have faster rise times and peak earlier than soft X-rays in the 2-16 Å range, the data available to date show that on the average the start time of the 2-16 Å X-rays occurs earlier than the start times for these other types of data. The early start times and large percentage increase of 2-16 Å X-rays make this radiation the best suited for the automatic detection of solar flares for the present state of the art of solar radiation measurements.

KEY WORDS

Solar flare
X-rays
Solar radio bursts
Extreme ultraviolet
H-Alpha

EARLY DETECTION OF A SOLAR FLARE
A STUDY OF X-RAY, EXTREME ULTRAVIOLET, H-ALPHA, AND
SOLAR RADIO EMISSION FROM SOLAR FLARES

by

R. F. Donnelly

1. INTRODUCTION

The study reported here originated from a question that arose from NASA's manned Apollo-Telescope-Mount (ATM) program. In the ATM orbiting solar observatory, it was planned to use X-ray measurements to detect solar flares of Hα importance ≥ 1 (Mr. Art White, NASA, Huntsville, private communication), in order to start high time-resolution measurements of the flare. The question was "Are there any other measurements that would improve the detection of solar flares at the earliest possible moment?" This question in turn led to many other questions, some of which are shown in figure 1 along with an indication of the data used to answer the questions.

The results of the comparison of this after-the-fact flare data are discussed in section 2. The qualification "after-the-fact" is important. It refers to the fact that the data were timed after the flare had occurred. The "after-the-fact" start time therefore would tend to precede the time when any practical flare alarm system would be set off. This should be kept in mind when reading section 2.

In section 3, the results of an analysis of Explorer-30 X-ray flare data using digital-computer simulation of the presently planned X-ray a alarm system are discussed. This analysis provided not only a coarse evaluation of the planned alarm system but also some information on the time delay between the after-the-fact start time and the time when the flare alarm was set off.

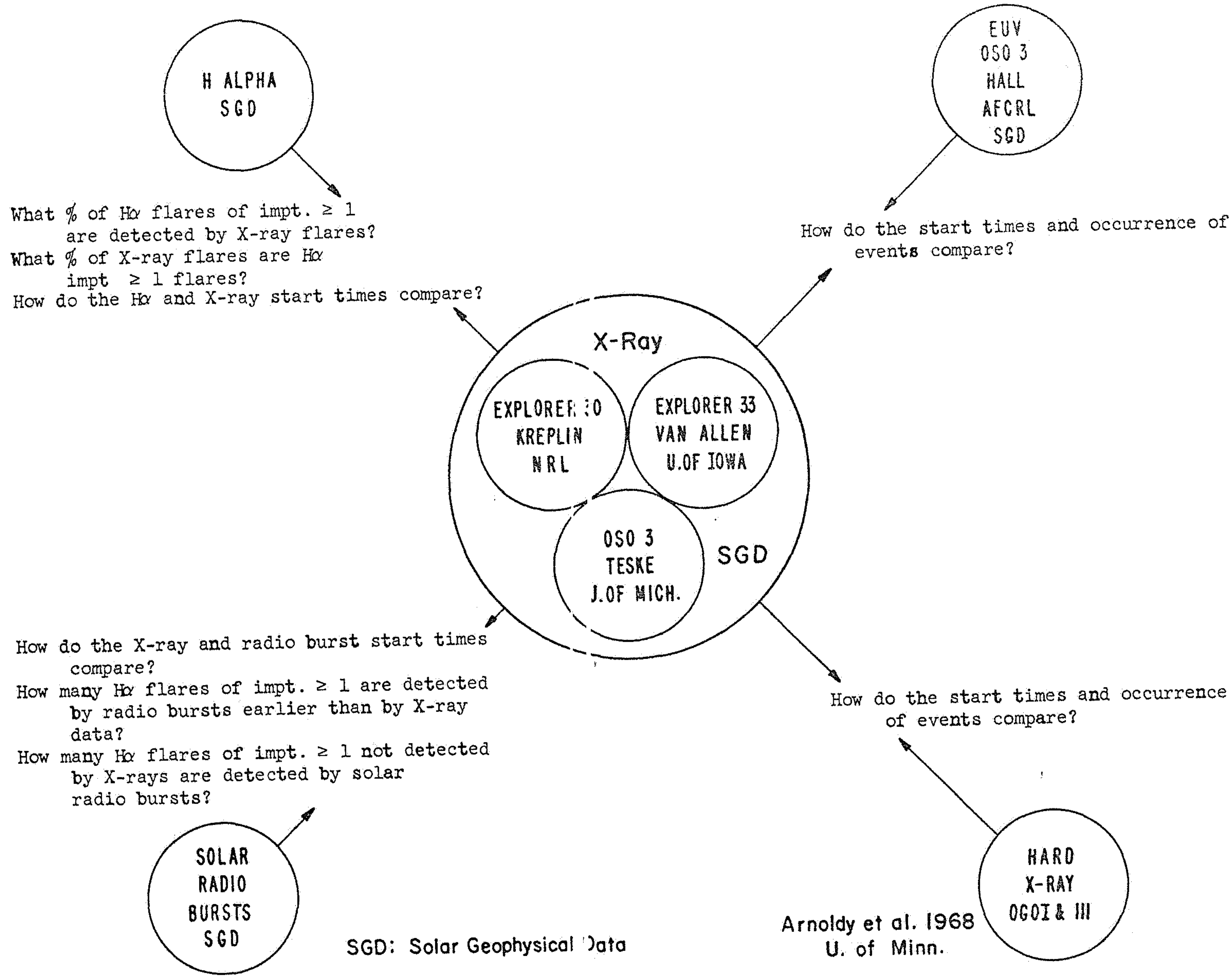

Figure 1. Questions and data involved in the ATM flare alarm study.

2. COMPARISON OF AFTER-THE-FACT X-RAY, SOLAR RADIO, Hα, AND EXTREME ULTRAVIOLET FLARE RADIATION

2.1 Sources of Data

Published X-ray data from several different satellites listed in table 1 were used in order to increase the number of events in our study and to avoid forming conclusions that might be influenced by biases in the instrumentation or data processing techniques of any one satellite experiment. The data reported in Solar Geophysical Data are preliminary reports, which appear to be slightly incomplete and contain a few errors; but these are minor problems that are believed not to have influenced the main results of this study. The timing accuracy given in table 1 for the available X-ray data was certainly less than desired.

The Hα flare data studied were those published in Solar Geophysical Data (SGD). The use of Hα data is somewhat subjective since the reports from different observatories are often in disagreement and the weighting and averaging of the different reports is not a simple one. The faults in Hα flare reports discussed by Warwick (1965), Sawyer (1967), and Dodson and Hedeman (1968) have not been removed from the present study, but their possible influence on the results will be discussed later. Hopefully, the quality of the H-alpha observations used in this study may be slightly better than the earlier data considered in the papers cited above as a result of their criticism.

The solar radio data used in this study are also from SGD. Since the radio observatories that report their data in SGD are located in the continental United States, Canada, and Argentina, only the 1200 to 2400 UT period is well represented. Although radio bursts are classified into numerous types of events, the present study is only concerned with whether any type of radio event was observed for a particular flare and what the earliest start time was of the associated radio events.

Table 1. X-Ray Data Sources

Satellite	Approximate Wavelength Ranges (Å)	Principal Investigator of X-Ray Experiment	Type of Data	Reference
Explorer 30	0.5-3 1-8 8-16 44-60	R. Kreplin Naval Research Laboratory Washington, D.C.	List of observation periods. List of occurrence of outstanding events. No timing of X-ray flares. No information on the wavelength range observed. Used data from April and May 1966 and from February through September, 1967.	*Solar Geophysical Data* (published by ESSA)
Explorer 33	2-12	J.A. Van Allen Department of Physics and Astronomy The University of Iowa Iowa City, Iowa	List of X-ray flares with start & maximum times & the ratio of the peak-flare flux to the preflare flux for flare when this ratio was ≥ 4. Some information on periods of no observation. Used data from July 1, 1966 through July, 1967. Timing accuracy $\approx \pm$ 82 sec.	*Solar Geophysical Data*
OSO 3	8-16	R.G. Teske Department of Astronomy University of Michigan Ann Arbor, Michigan	List of observing periods with notes on events of amplitude ≥ 0.002 ergs cm^{-2} sec^{-1}. List of outstanding events with start, maximum & end times & the preflare & peak-flare flux. Used data from March through August, 1967. Timing accuracy $\approx \pm$ 2 min.	*Solar Geophysical Data*

Table 1. X-Ray Data Sources (Cont.)

Satellite	Approximate Wavelength Ranges (A)	Principal Investigator of X-Ray Experiment	Type of Data	Reference
Vela	0.5-4 0.5-10	J.P. Conner Los Alamos Scientific Laboratory University of California Los Alamos, New Mexico	List of X-ray flares with timing. Timing accuracy $\sim$ 1 min.	Conner, et al. (1964)
OGO I & III	$<$ 0.6 A	R.L. Arnoldy, S.R. Kane, & J.R. Winckler School of Physics and Astronomy University of Minnesota Minneapolis, Minnesota	An atlas & list of hard X-ray events	Arnoldy, et al. (1968 a & b)

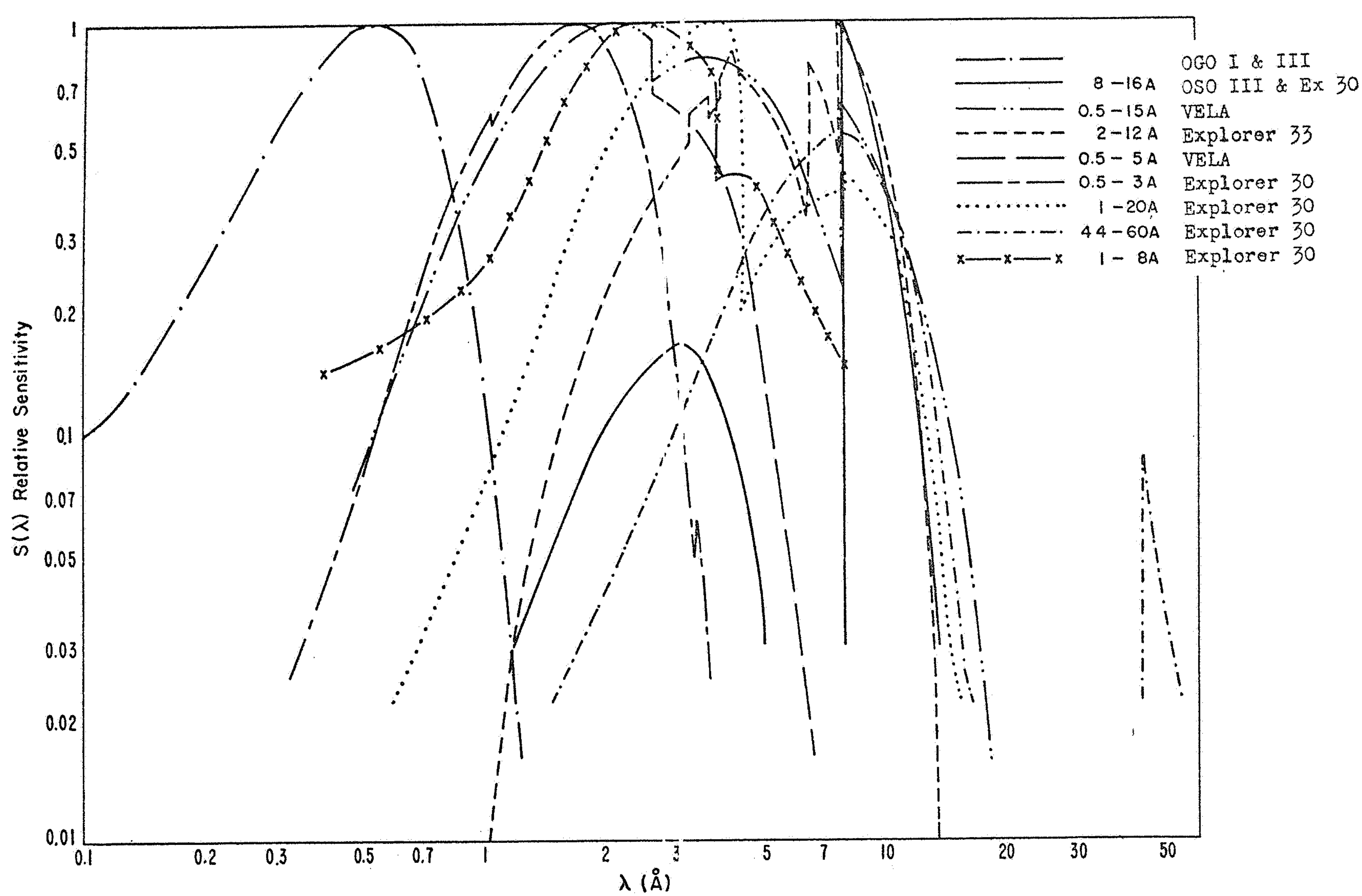

Figure 2. Relative wavelength response of the X-ray detectors.

2.2 Intercomparison of Soft X-Ray Data

According to Dr. L. Van Speybroeck of American Science and Engineering the ATM X-ray alarm will utilize about 1-8 Å measurements. Figure 2 shows the normalized relative wavelength response of the radiation detectors corresponding to the various X-ray data involved in the present study. Clearly the 0.5-3 Å and 44-60 Å Explorer-30 data, the OGO data, and the Vela 0.5-5 Å data cannot be considered to be representative of the 1-8 Å X-ray measurements proposed for the ATM alarm system; these data will be used for other purposes. The 1-8 Å and 8-16 Å Explorer-30, 2-12 Å Explorer 33, and 8-16 Å OSO-3 data on the other hand will be assumed to have characteristics about the same as the 1-8 Å ATM alarm measurements will have. The Explorer 30, Explorer 33, and OSO-3 X-ray data were examined for flares when any two of these satellites made X-ray observations to find out whether the observations from each satellite were consistent with the observations from the other satellites.

Only 13 flares were found when both Explorer 33 and OSO-3 made X-ray observations. In each case, both experimenters reported X-ray flares, but the timing was only in fair agreement. The average difference in start times was about 0.8 min (with a rather large standard deviation σ of 4.8 min). The average difference in peak times was 1.5 min (σ = 10.4 min). In both the start and maximum timing, the OSO-3 timing preceded the Explorer 33 timing on the average. Some of the differences in timing could very well be due to the differences in their relative wavelength responses, coupled with the time dependence of the flare radiation varying over the 2-16 Å range.

The Explorer 33 and 30 data were examined to learn how well the occurrence of reported X-ray flares agreed when both satellites made observations. There were 25 cases when the observation period of Explorer 30 overlapped by a minute or more the start-to-maximum time of the X-ray flares reported from Explorer 33. Of these few cases, 84 percent were reported as outstanding events in the Explorer 30 data. The reverse comparison shows that a large percentage of Explorer 30 outstanding events occurred when Explorer 33 did not report an X-ray flare (when "no observations" was not reported). This was expected since only X-ray flares with a flux greater than or equal to 400 percent were reported from the Explorer 33 data. Also, the reporting of short periods of no solar X-ray observations appeared to be incomplete for the Explorer 33 data.

Similarly, 89 percent of the cases when Explorer 30 made X-ray observations when OSO-3 observed an X-ray flare were reported as an outstanding event in the Explorer 30 data. Conversely, 50 percent of the outstanding Explorer 30 events that occurred when OSO-3 made X-ray measurements were reported as an outstanding event in the OSO-3 data. In conclusion, it appears that smaller X-ray flares were reported from the Explorer 30 data than from the OSO-3 and Explorer 33 data. These three sets of data appear to be in good agreement on the occurrence of X-ray enhancements ≥ 0.005 ergs cm^{-2} sec^{-1} when observations were being made.

2.3 Start-to-Maximum Time and Intensity of Soft X-Ray Flares

Figure 3 shows the rather spread-out distribution of start-to-maximum times for the X-ray flares observed by Explorer 33 and OSO-3. A few events with very large start-to-maximum times are probably composed of several superimposed X-ray flares since several Hα flares were reported during these events. The distribution curves show that the soft X-ray start-to-maximum times are clustered mainly in the 3-18 min range. According to Sengupta and Van Allen (1968) the rising portion of the Explorer 33 X-ray observations can be reasonably well fit with a function of the form $1 - \exp(-t/\tau_r)$, where τ_r varies from flare to flare but is typically about 5 min.

Figure 4 shows that most of the reported X-ray flares are rather small and that the published list of OSO-3 outstanding events includes quite a few events smaller than reported for Explorer 33. The number of X-ray flares observed appears to be roughly inversely proportional to the ratio of the peak X-ray flux to the preflare flux for flare enhancements

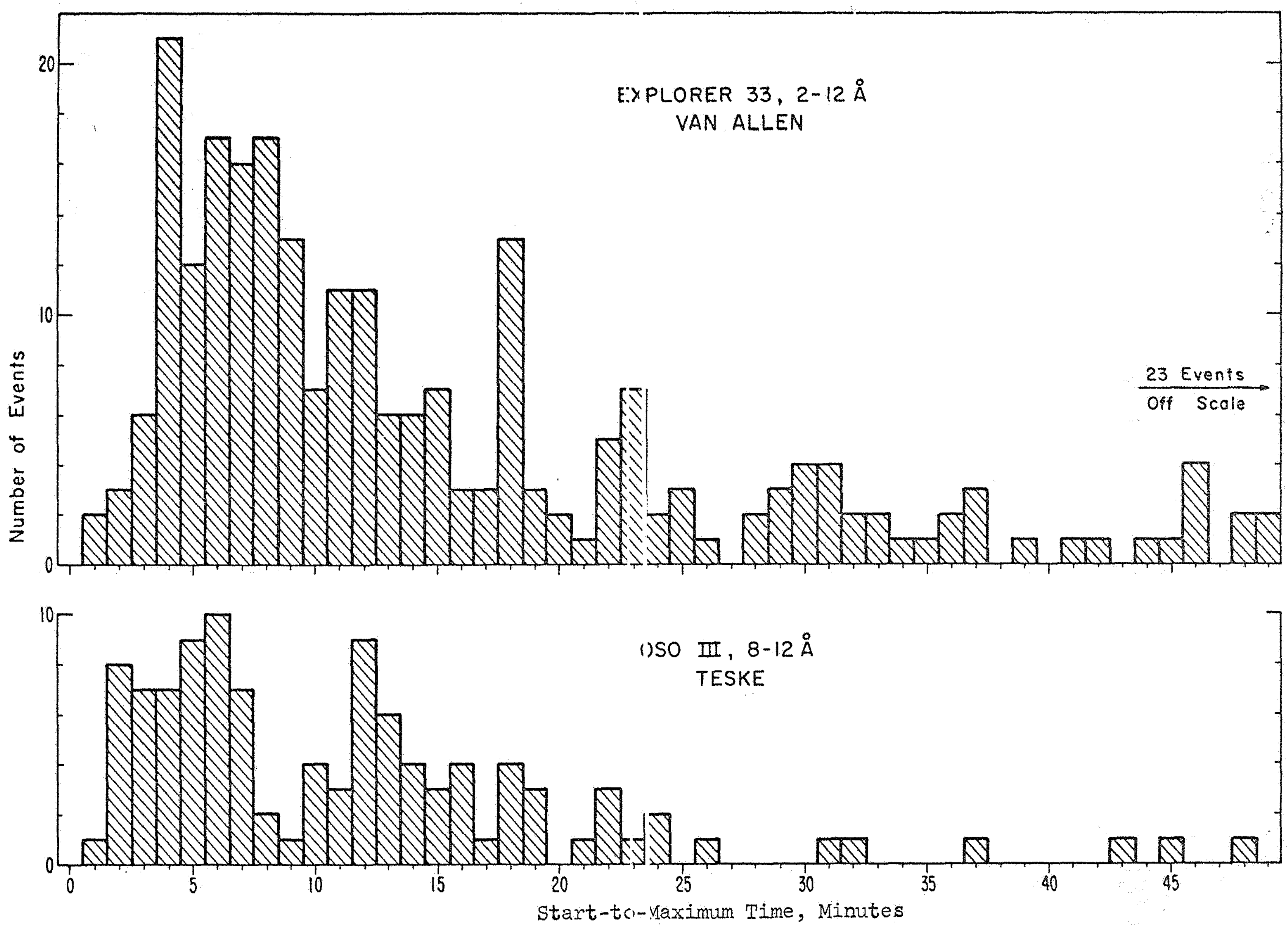

Figure 3. Distribution of start-to-maximum times of X-ray flares.

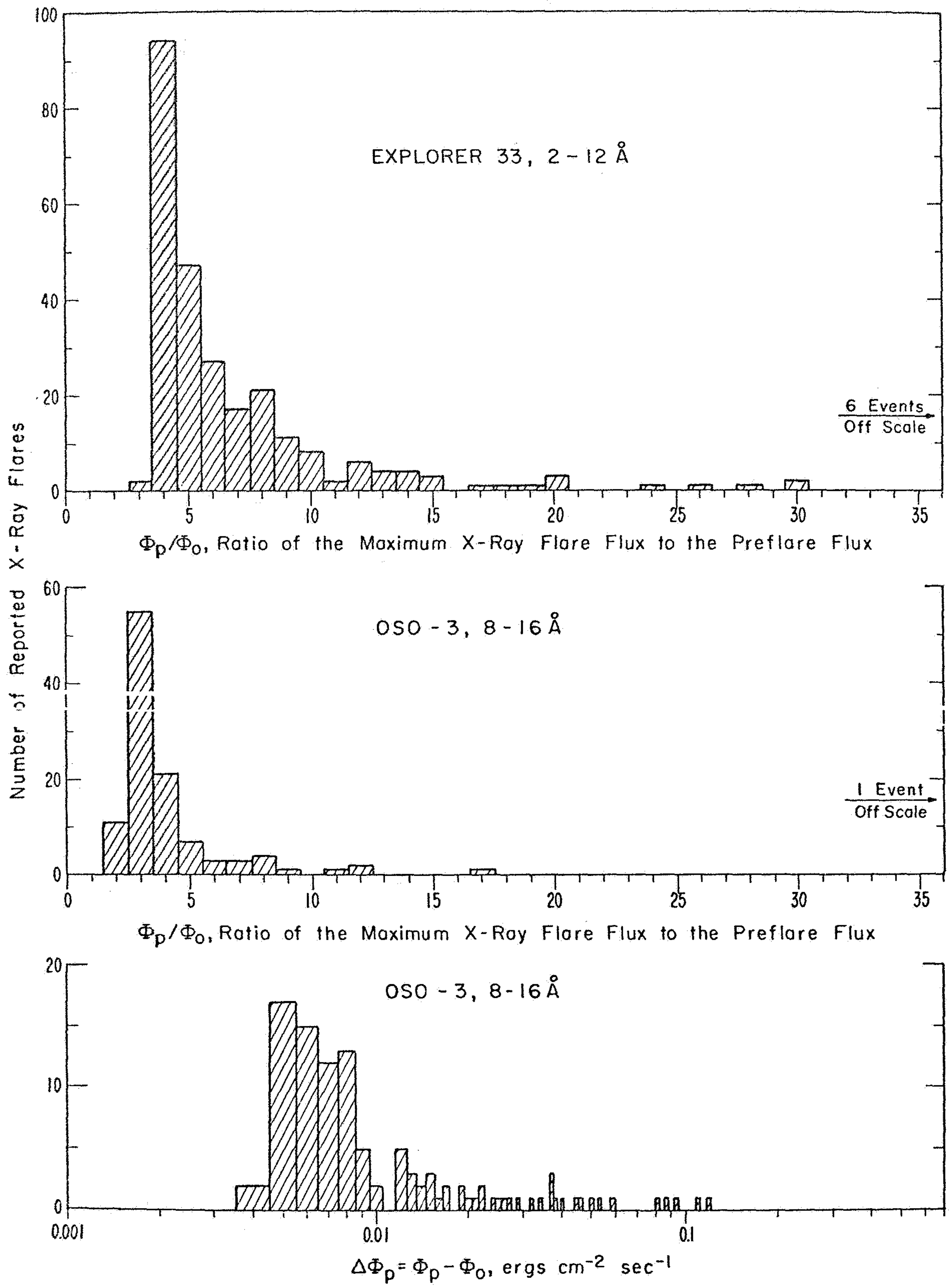

Figure 4. Distribution of the intensity of X-ray flares.

above the minimum reported values. An average of the flux increases for the flares reported for a particular satellite would be strongly dependent on the minimum size reported and, therefore, would not be too meaningful.

2.4 Comparison of Occurrence of Soft X-Rays and Hα Flares

Figure 5 shows (1) that most of the X-ray flares reported from the Explorer 33 data for which the Hα flare was unambiguously* identified are accompanied by H-alpha flares of importance 1 and greater; and (2) that nearly all of these have either normal or bright intensities. These trends are stronger for the larger X-ray flares with an increased tendency towards the flare intensity being bright rather than normal. The OSO-3 data in figures 6, 7, and 8 also show that these results are a function of the intensity of the X-ray flare.

For the Explorer 30 outstanding X-ray events about 20 percent were not accompanied by a reported Hα flare. Most of these occurred when "no flare patrol" was not reported. Figure 9 shows the distribution of the 80 percent with reported Hα flares. The results in figure 9 are consistent with the dependence on the X-ray flare intensity found in figures 5-8, and with the conclusion in section 2.2 that the reported Explorer 30 outstanding events include smaller X-ray flares than the Explorer 33 and OSO-3 lists of X-ray flares.

Figure 10 shows the association of OSO-3 soft X-ray flares with Hα flares as a function of importance and intensity. Considering the X-ray flare intensity dependence found in figures 5-8, the results in figure 10

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*Twenty-six percent of the Explorer 33 X-ray flares were excluded from the data used in figure 5 because the Hα flare was not unambiguously identified. These included some events where "no flare patrol" was reported, some when no Hα flares were reported and "no flare patrol" was not reported, some where several flares occurred during the X-ray flare, and some where the Hα flare reports from different observatories for the same flare were too much in disagreement to support a simple consensus of the reports. Sengupta and Van Allen (1968) report that every Explorer 33 X-ray flare of peak intensity greater than 3.0×10^{-4} ergs cm^{-2} sec^{-1} in the 2-12 Å range was accompanied by an Hα flare.

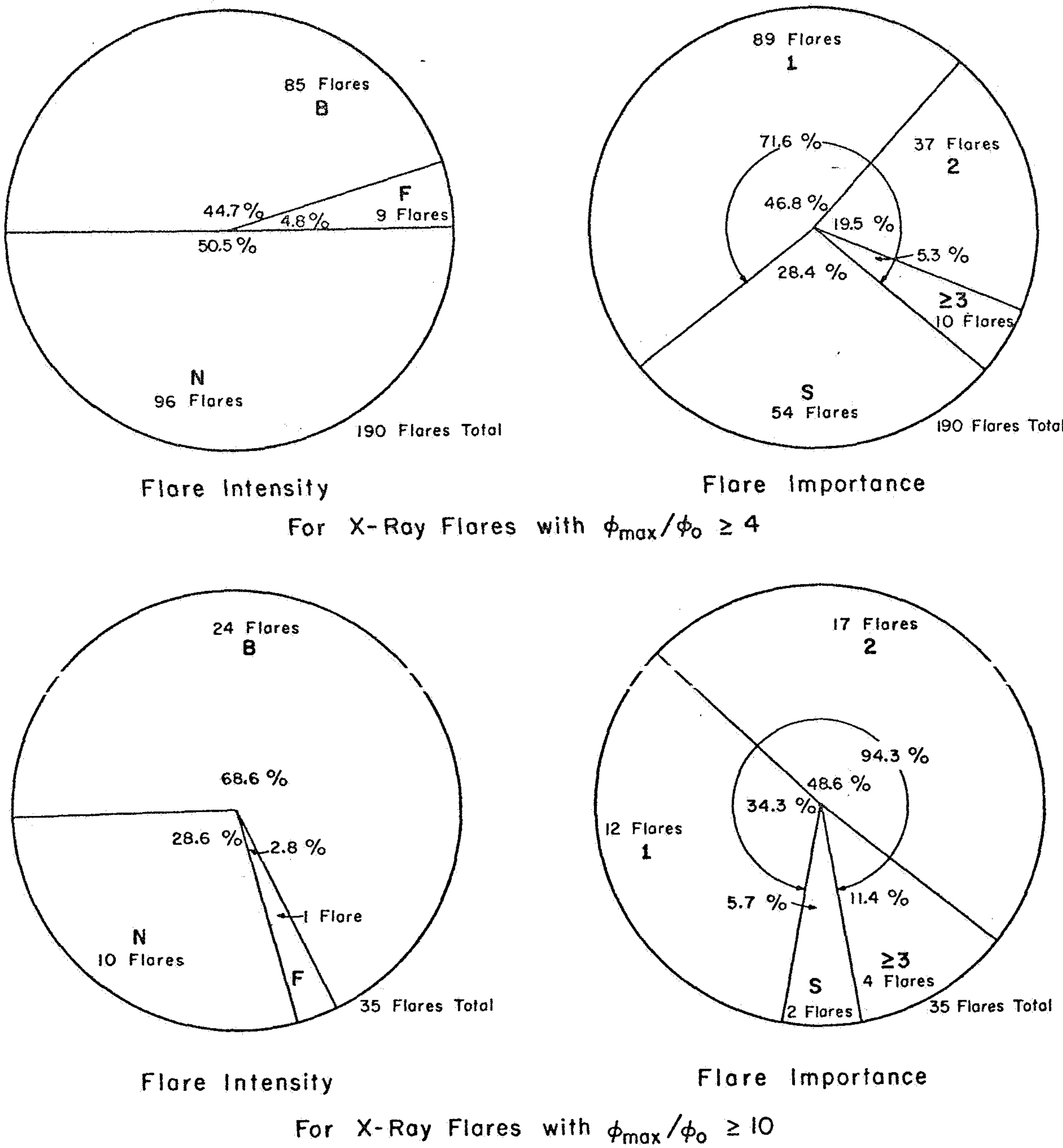
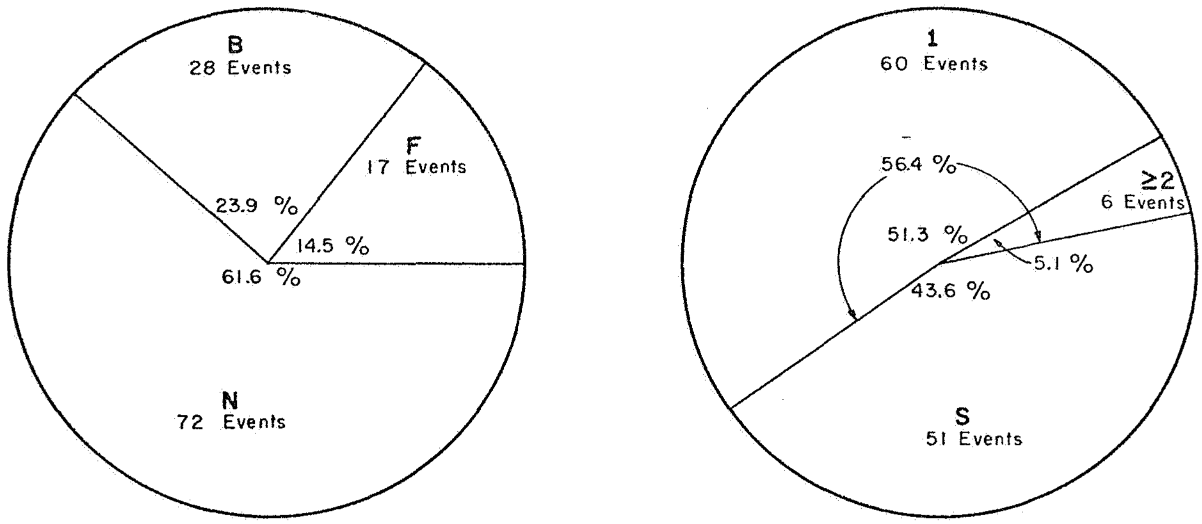
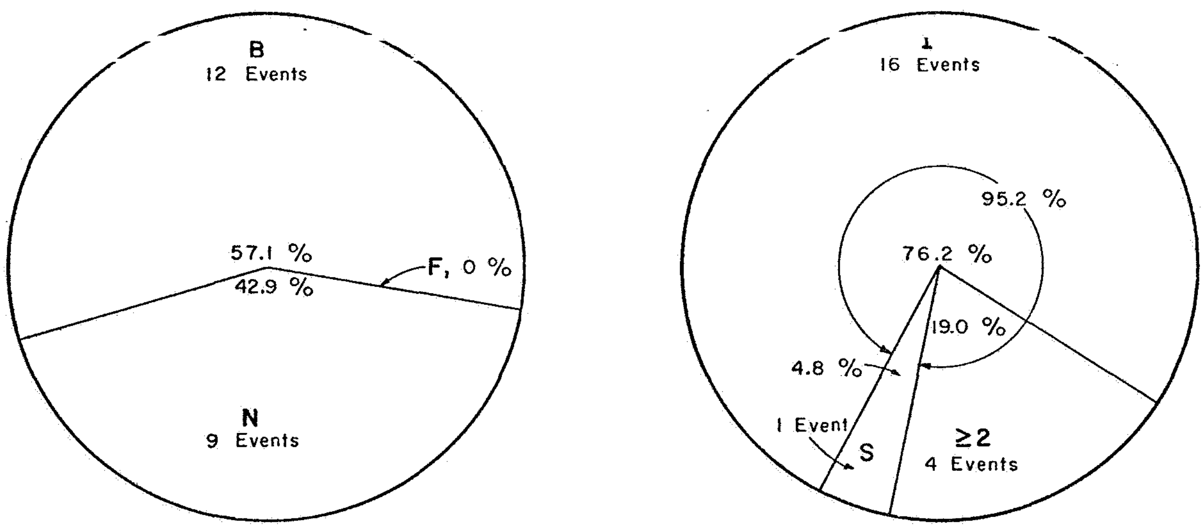


Figure 5. Distribution of Explorer 33 X-ray flares as a function of Hα importance and intensity.



Flare Intensity Flare Importance

For X-Ray Flares with $\Delta\Phi_{8\text{-}16\,\text{Å}} > 0.002$ ergs cm^{-2} sec^{-1}



Flare Intensity Flare Importance

For X-Ray Flares with $\Delta\Phi_{8\text{-}16\,\text{Å}} > 0.025$ ergs cm^{-2} sec^{-1}

Figure 6. Distribution of OSO-3 outstanding X-ray flares as a function of Hα importance and intensity.

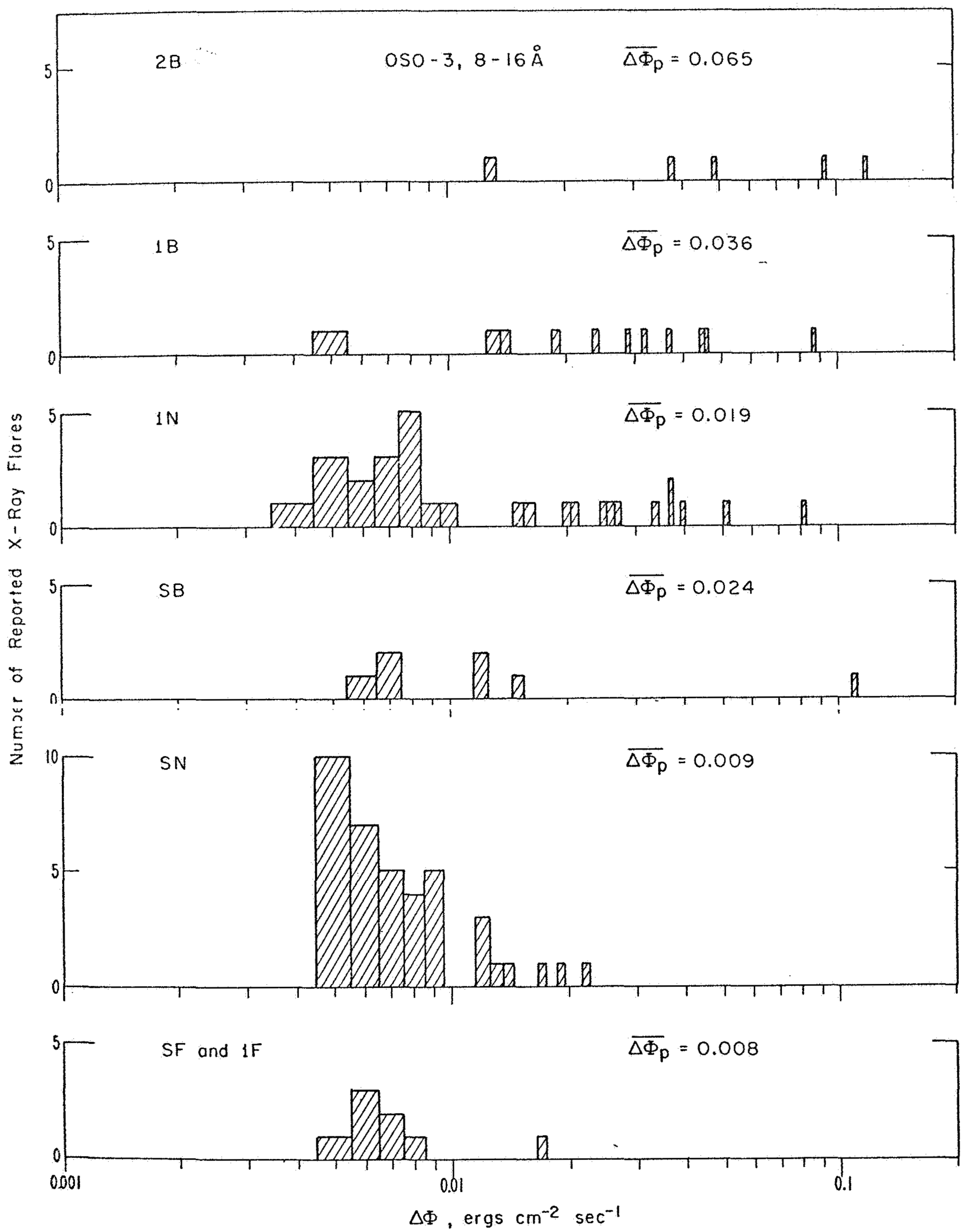


Figure 7. Distribution of X-ray flux enhancement as a function of Hα importance and intensity.

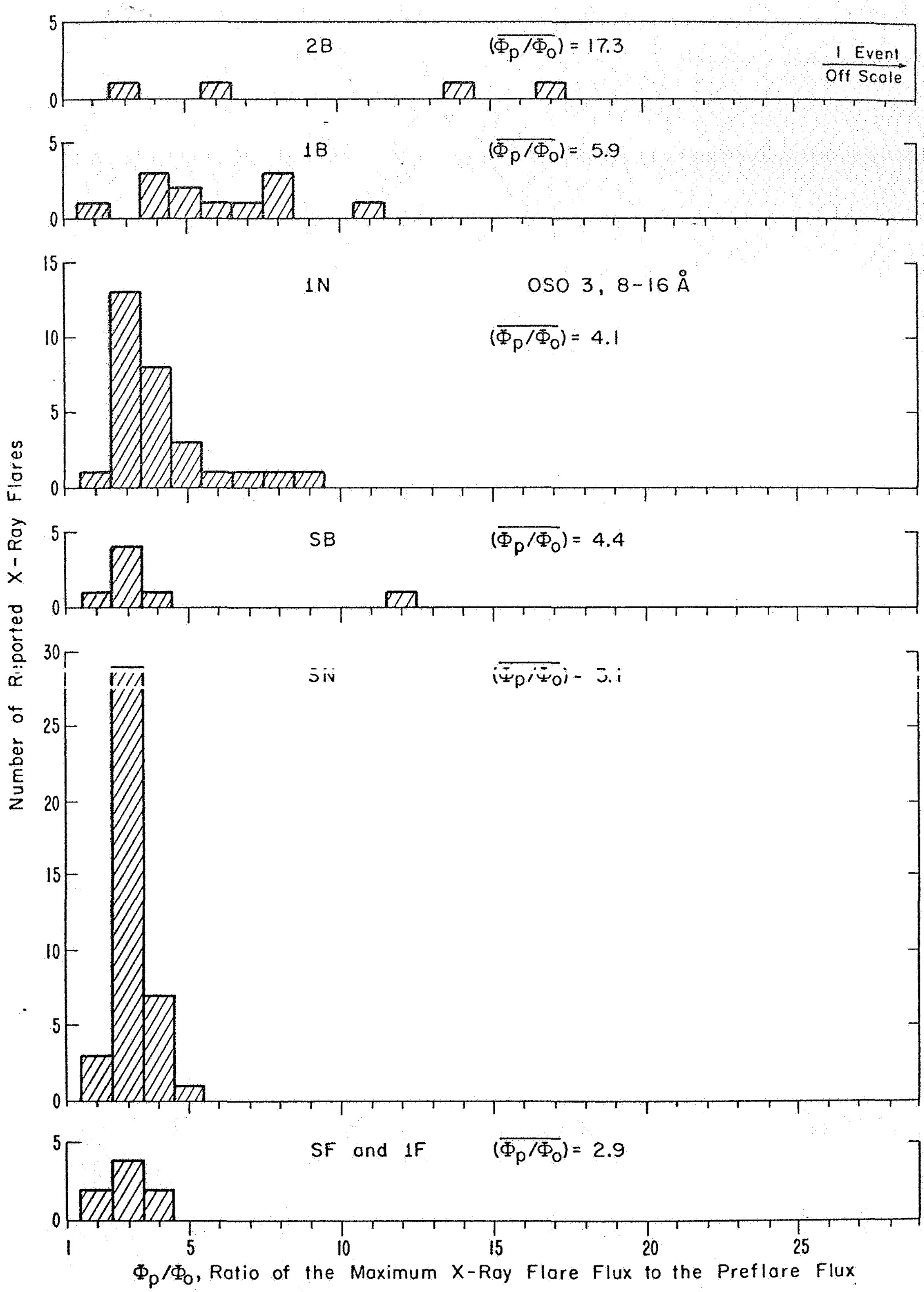


Figure 8. Distribution of the ratio of the peak X-ray flare flux to the preflare flux as a function of Hα importance and intensity.

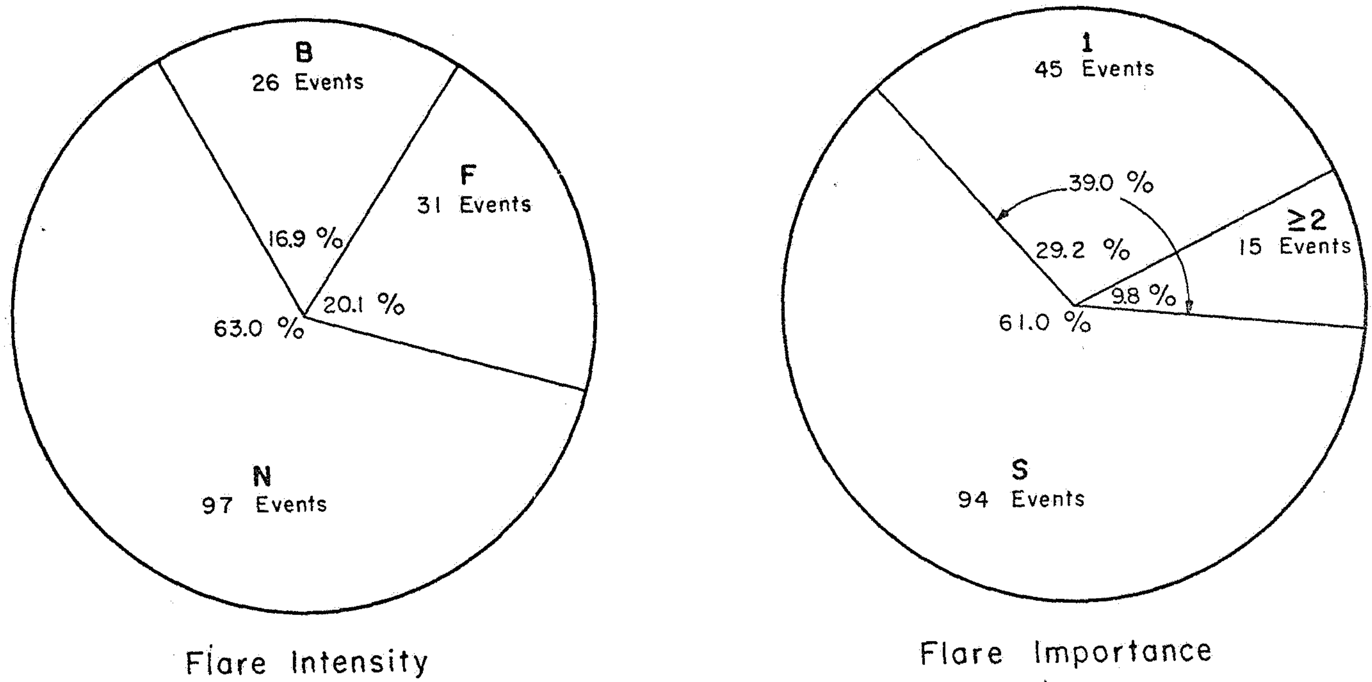


Figure 9. Distribution of Explorer 30 X-ray flares as a function of Hα importance and intensity.

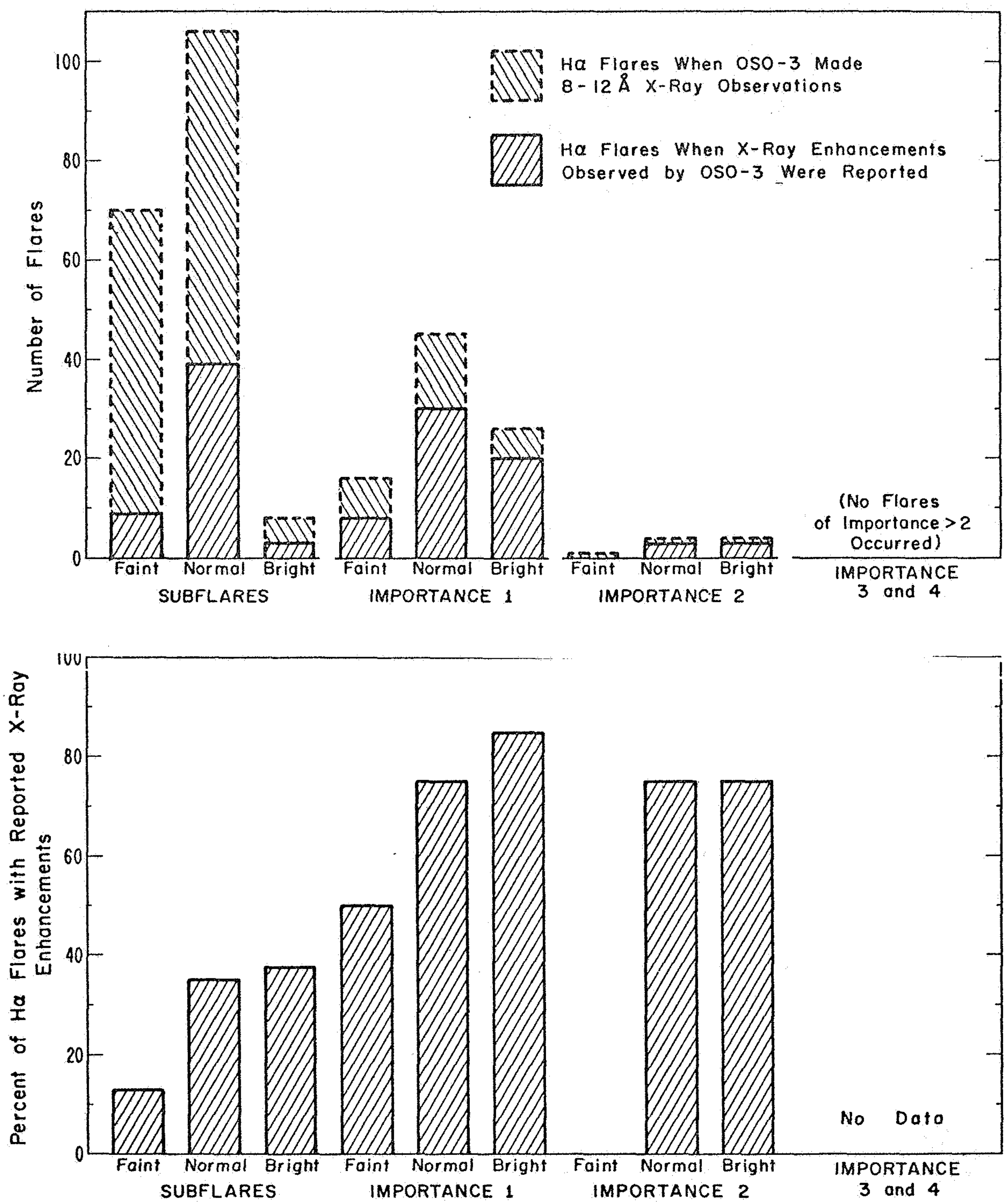


Figure 10. The association of soft X-ray flares with Hα flares as a function of Hα importance and intensity.

are undoubtedly dependent on the minimum size of X-ray enhancement reported as an event. There is a trend toward an Hα flare having an increasing likelihood of being accompanied by an X-ray flare for increasing Hα importance and intensity. This trend was also evident from the Explorer 30 data. About 69 percent of the Hα flares of importance 1 or greater are accompanied by OSO-3 X-ray enhancements greater than 0.002 ergs cm^{-2} sec^{-1}; if faint intensity flares are excluded the rate is up to about 73 percent. Dodson and Hedeman (1968) have reported that three-fourths of the flares during the IQSY reported in the Quarterly Bulletin on Solar Activity as Hα importance 1 or greater would not have been rated with such a high importance if all of the available flare patrol data had been carefully scrutinized. If the overrated data were removed from the present study, the percentage of Hα flares of importance 1 or greater which are accompanied by reported X-ray enhancements would probably be much greater than 69 percent. Indeed, many of the flares encountered in this study, which were reported to be of importance 1 or greater and were not accompanied by a reported X-ray event even though X-ray measurements were being made, were cases where only one observatory reported the flare. Usually these were observatories having a reputation of overrating the Hα flare importance.

2.5 Solar Radio Emission

Perhaps the best contender with X-ray data for automatic detection of the start of a solar flare is the solar radio emission at centimeter wavelengths or shorter. Solar radio bursts have rapid rise times; they usually occur early in the flare; and the percentage increase in the radio flux is fairly high. All of these factors are desirable for automatic detection systems. Figure 11 shows the distribution in rise times of radio bursts as a function of transmission frequency. About half of the radio bursts at all of the frequencies shown have start-to-maximum times less than 1.5 min. Hence the radio bursts have start-to-maximum times that are much shorter than the soft X-ray data in figure 3. One possible reason for this is that the start-to-maximum times for both

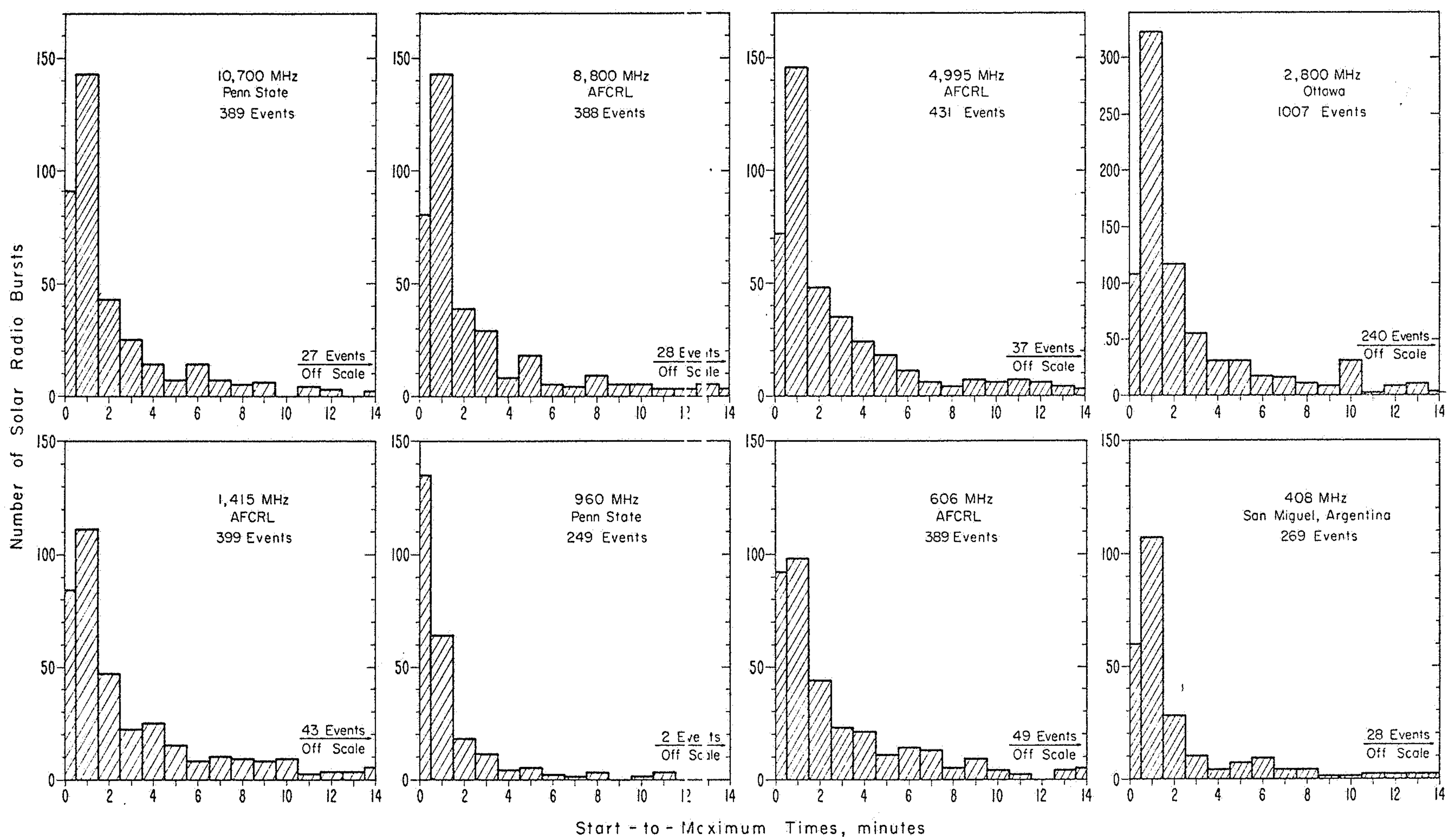


Figure 11. Distribution of start-to-maximum times of solar radio bursts.

the slow rise-and-fall and fast solar radio bursts are often reported for the same event, whereas the soft X-ray enhancements are each reported as one event. However, this is not the main reason. The soft X-ray enhancements I have examined do not have such distinct parts, at least for wavelengths greater than 2 Å. They seem to have at most a period of faster rise during the fast solar radio bursts. Neupert et al. (1967) found during a flare of importance 2b that the X-ray emission lines for the highest stages of ionization (Fe XXIV - Fe XXV) increased most rapidly at the onset of the flare, while the lower stages of ionization (Fe XVII - Fe XX) were observed later in the event. Perhaps certain lines in the soft X-ray range do have a fast component corresponding to the fast solar radio bursts, but the net radiation observed by a broad-band soft X-ray detector at $\lambda > 2$ Å does not. [The hard X-ray observations ($\lambda < 1$ Å) do contain fast bursts closely associated with the centimeter wavelength solar radio bursts, at least for the first such radio burst of the flare (Arnoldy, et al., 1968a)]. In conclusion, the solar radio bursts generally have much shorter start-to-maximum times (0.2-2 min) than do the broad-band soft X-ray measurements (3-18 min).

In section 2.4, it was found that about 69 percent of the solar flares of Hα importance 1 or greater that occurred when OSO-3 made measurements were accompanied by a reported X-ray enhancement. The flares not detected by X-rays were examined to determine whether they could have been detected by solar radio measurements. Only 10 percent of the flares not detected by X-rays were accompanied by solar radio bursts reported in Solar Geophysical Data (SGD), and these cases were only importance 1 flares with very small radio bursts. Taking the observation time bias of the SGD data into account, it appears that at best the percentage of flare of Hα importance 1 or greater that would be detected could increase from 69 percent to about 79 percent if very sensitive solar radio measurements were made in addition to the soft X-ray measurements. The flares added in this way would not be the most desirable ones. This same increase could probably be just as easily achieved by improving the soft X-ray measurements. Considering figure 6, the number of subflares detected would probably also increase.

It should be remembered, however, that the OSO-3 list of outstanding X-ray flares includes fairly small events. If the ATM X-ray flare alarm system were fairly insensitive so that it could not detect many of the OSO-3 reported X-ray flares, then the advantage of adding solar radio measurements would undoubtedly be increased.

2.6 Comparison of Timing of Soft X-ray Enhancements, Solar Radio Bursts, and $H\alpha$ Flares

The maximum solar radio emission and maximum $H\alpha$ emission usually precede the maximum of the soft X-ray enhancement by several minutes, as is evident from figures 12 and 13. Hence the solar radio bursts not only have fast start-to-maximum times but they also occur early in the rising portion of the soft X-ray flare. These facts make solar radio emission seem to be very suitable for the early detection of solar flares. On the other hand, figures 14 and 15 show that the reported start times for the soft X-ray enhancements precede the reported start times of the solar radio bursts on the average, as has been pointed out by Teske (1968a and b). Thus, it appears that soft X-ray measurements are potentially the best for the very early detection of solar flares.

Reported start times depend not only on the actual start of the event but also on the signal-to-noise ratio, the way the data are recorded, and the way they are processed. Figure 16 illustrates some of these difficulties. The noise includes noise from the electronics of the radiation detection system as well as any nonsolar signals. For example, the response of an X-ray detector to particles that collide with the satellite would be included as noise. For solar radio measurements, man-made interference, the antenna and receiver noise, the galactic radio noise, and the radio noise from the earth's atmosphere would all be included in the "noise" curve in figure 16.

If the noise level in figure 16 were increased by a factor of 10, the reported start time would probably be delayed. If the radiation detector response were highly variable before the flare, the reported

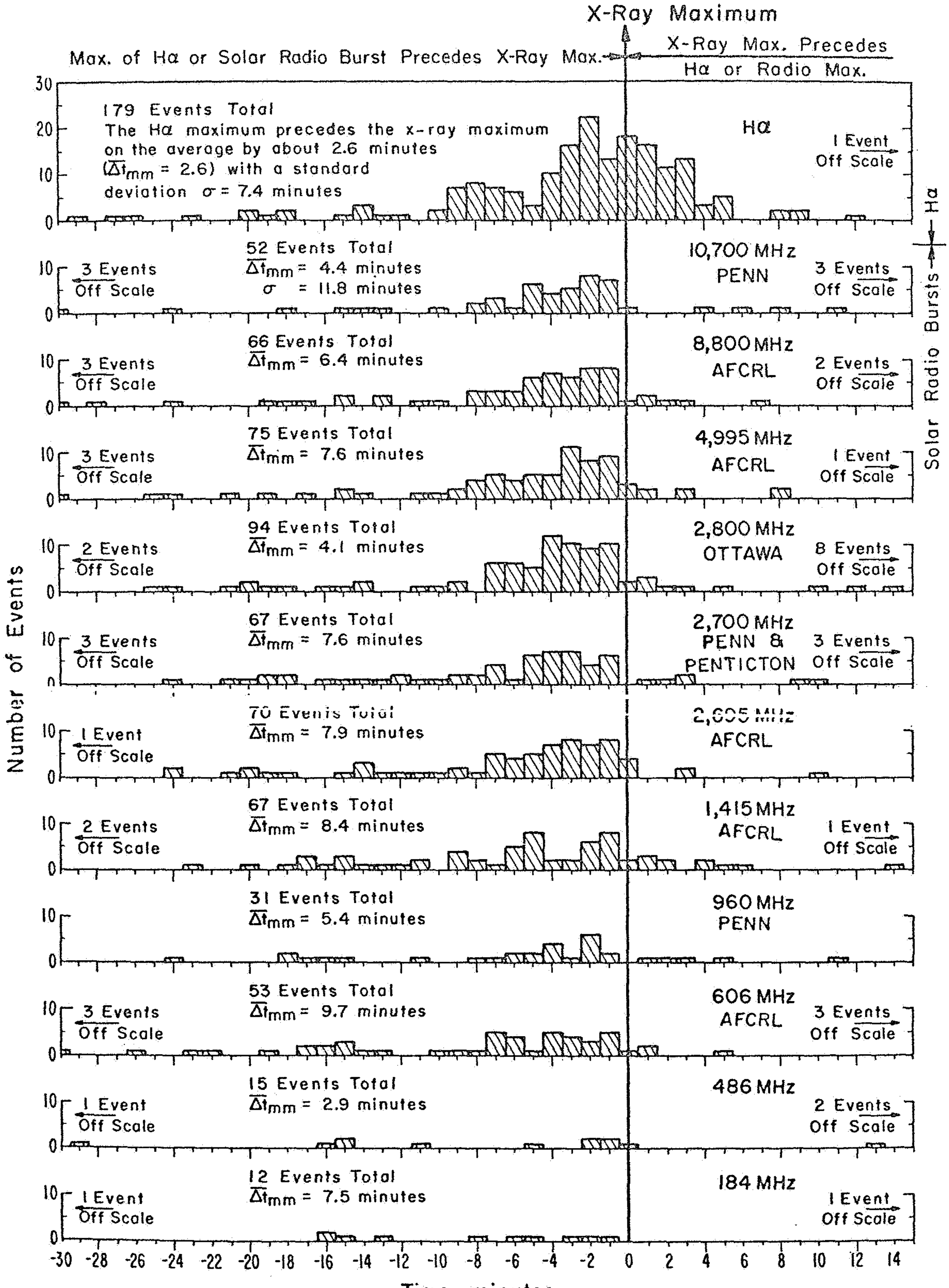


Figure 12. A comparison of times of maximum Hα flares and solar radio bursts with Explorer 33 X-ray enhancements.

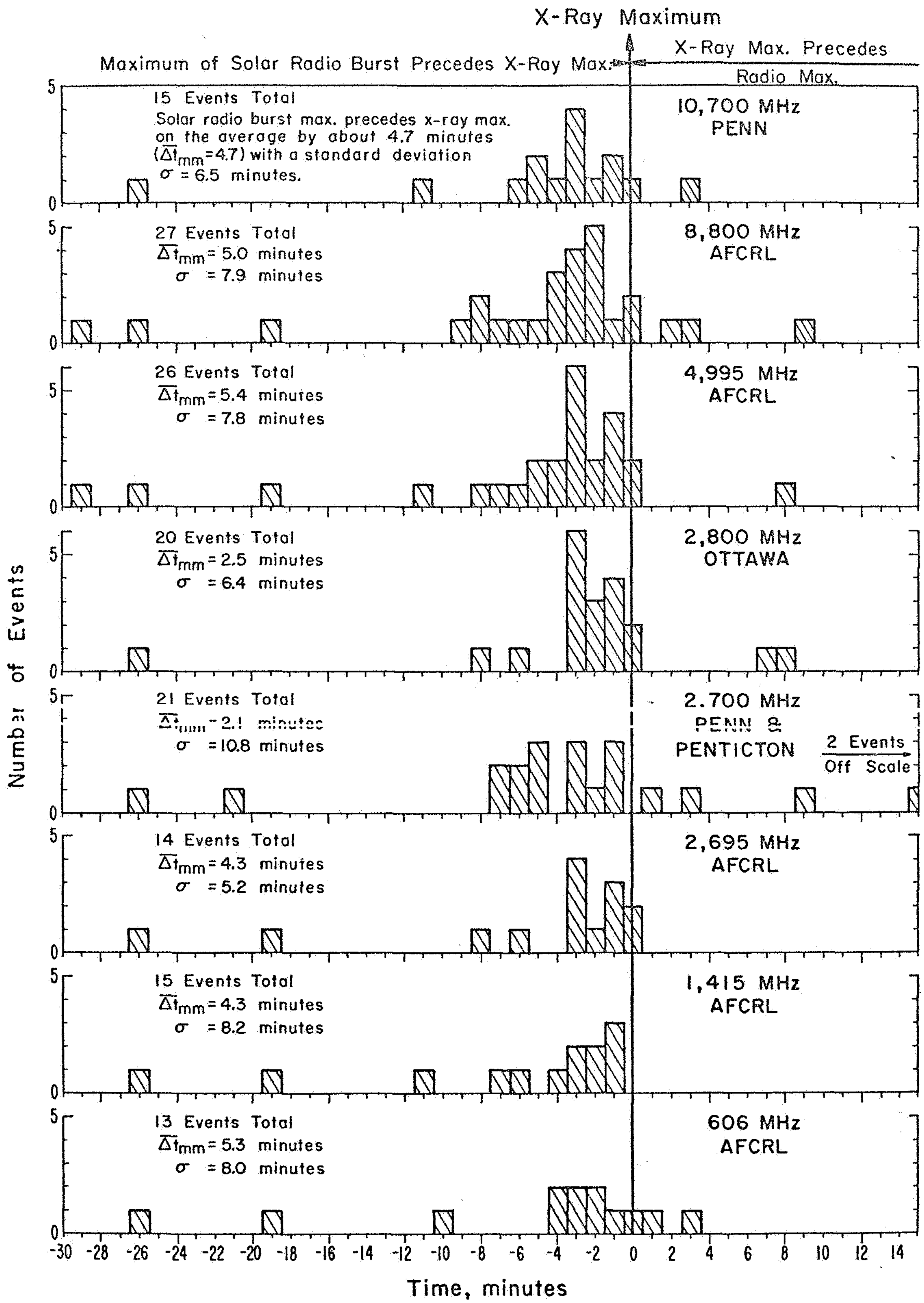


Figure 13. A comparison of times of maximum solar radio bursts with OSO 3 X-ray enhancements.

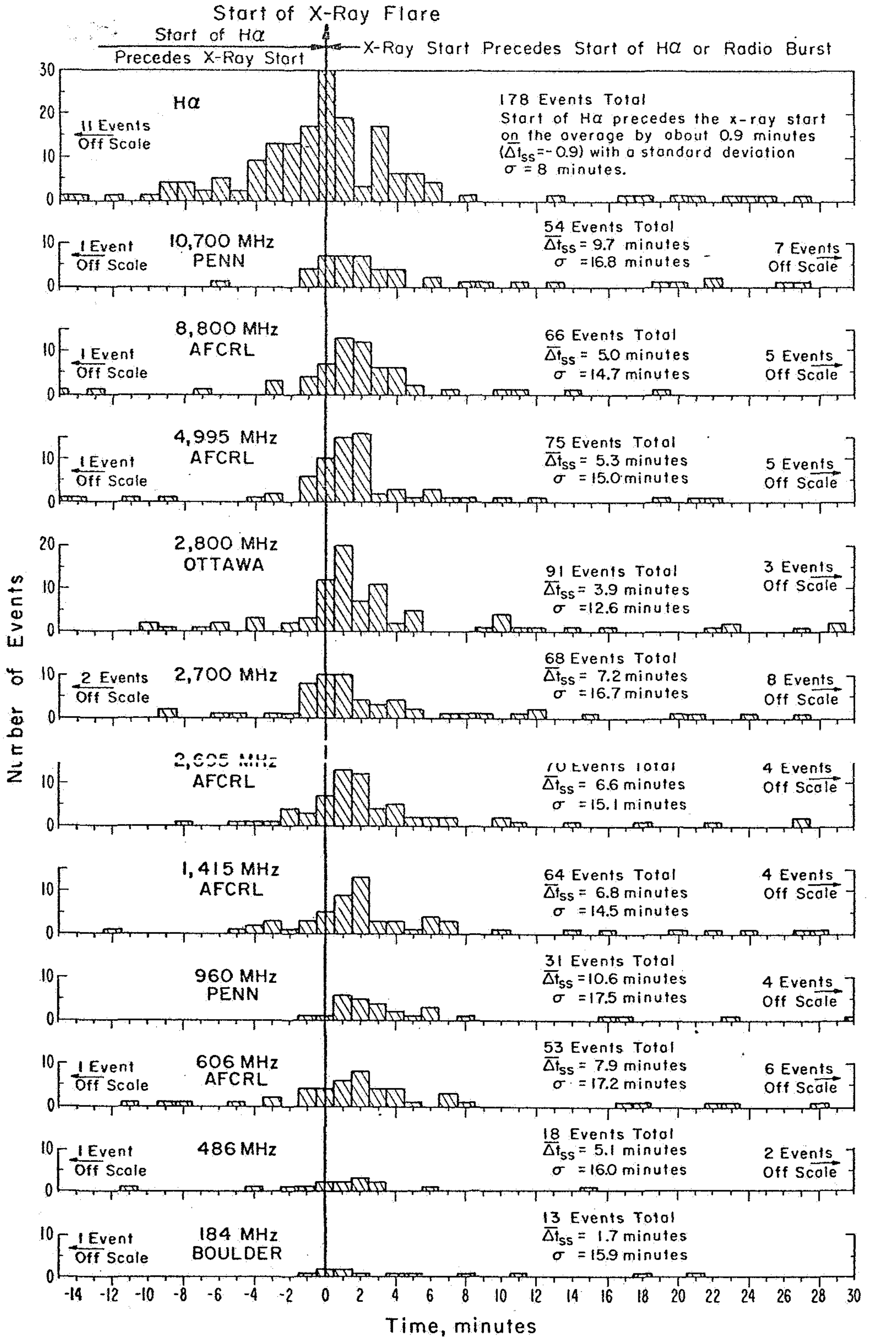


Figure 14. A comparison of start times of Hα flares and solar radio bursts with Explorer 33 soft X-ray enhancements. When more than one Hα or solar radio start time was reported, the start time used was the earliest reported.

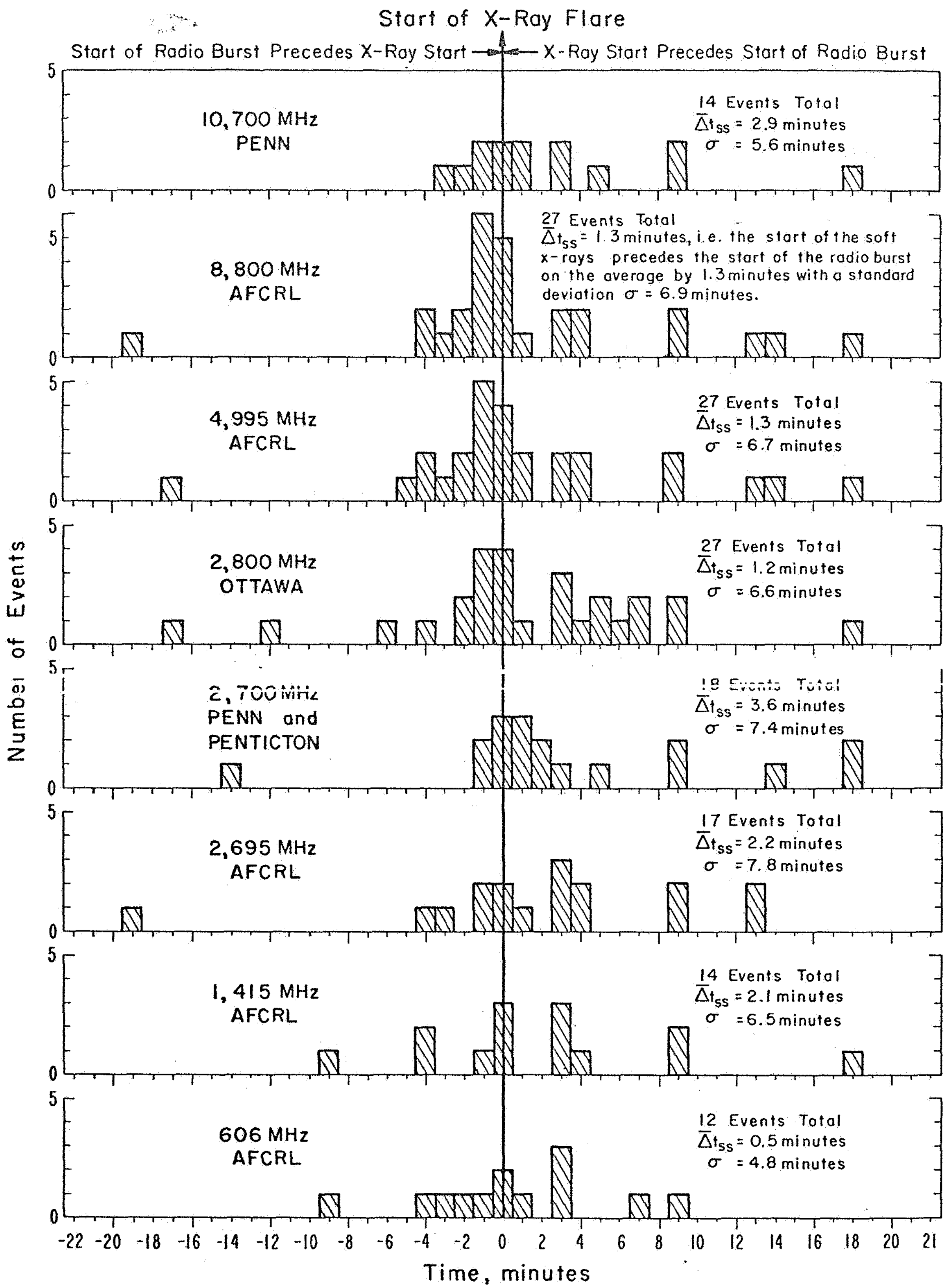


Figure 15. A comparison of start times of solar radio bursts with OSO 3 X-ray enhancements.

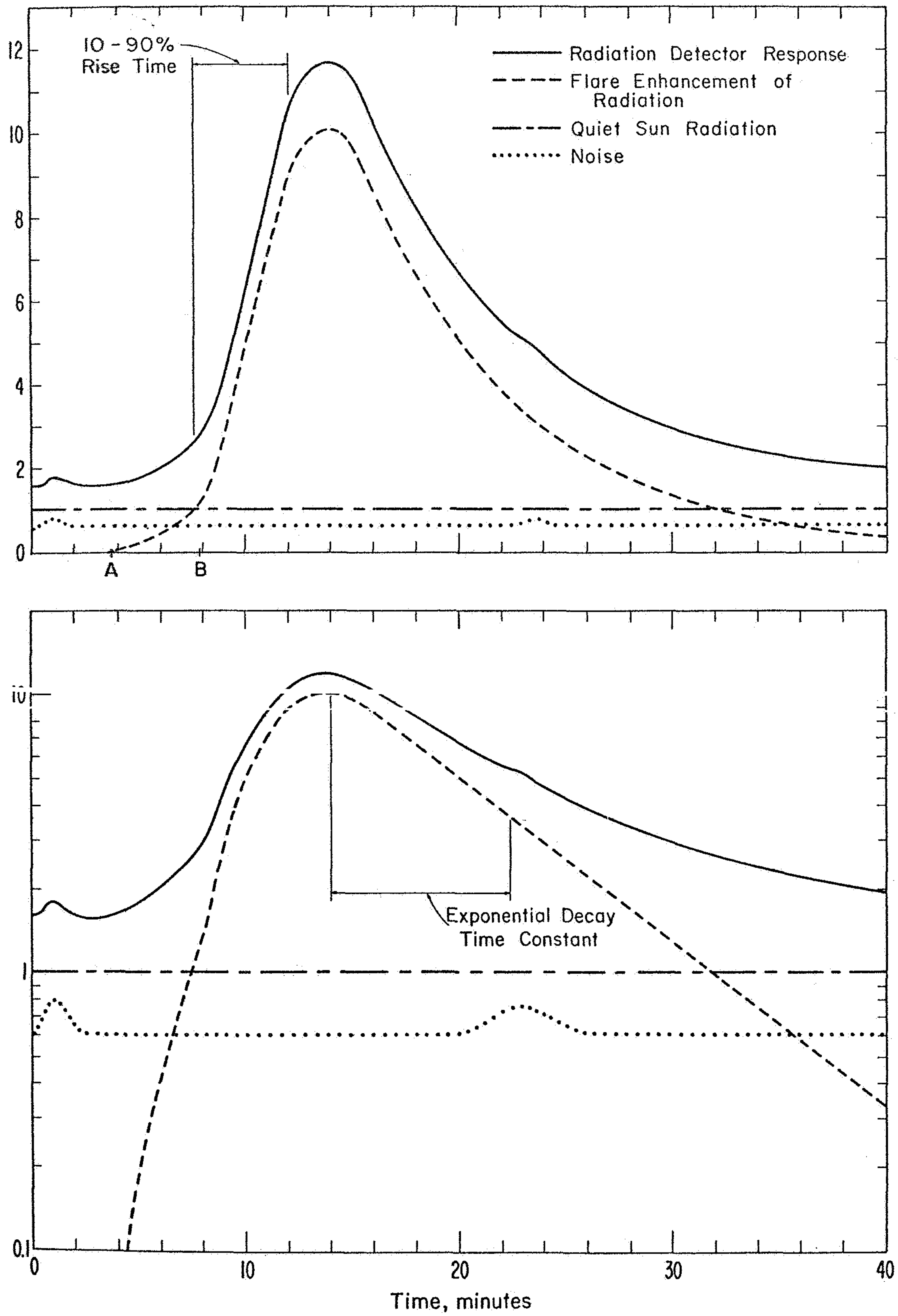


Figure 16. Difficulties in determining start, maximum, and end times.

start time would probably be delayed to the time when it was clear that the flare enhancement exceeded the preflare oscillations, or the data processor may use a linear extrapolation back to the average level before the flare (point B in figure 16). If the flare enhancement rises slowly at first and then rapidly, the start of the rapid rise might be reported if the noise level were high or if the data were recorded on a linear scale; on the other hand if the noise level were low and the data were recorded on a logarithmic scale, the start of the slow rise might be reported as the start time for the whole event. These are some of the problems in addition to the relatively large timing errors given in table 1 for the soft X-rays which might be affecting the start-time data used in this study. It is also difficult to measure the time of maximum radiation of soft X-ray enhancements because they are often rather smooth and flat topped. Since the solar flare radiation enhancements usually finish with a slow asymptotic approach to the preflare level, the end time is indistinct. Because of the above difficulties, the start-to-maximum data used in this study may give a rather poor indication of the rise times of the flare enhancement. Unfortunately, information on the 10-90 percent rise time was not available.

Despite the above problems in start-time data, I believe the trend deduced from figures 14 and 15 is too strong not to be valid, i.e., the measureable start time for soft X-rays generally precedes that for the solar radio enhancements. The several events for which copies of the solar radio and X-ray records were available showed the same results. For example, for the proton flare of July 7, 1966, the soft X-ray enhancement (2-12 Å) had started by 0023 UT (Van Allen, 1967) while the solar radio bursts in the 200-17,000 MHz range did not start until about 0026 UT or later.

Figure 14 also indicates that on the average the $H\alpha$ flare starts at about the same time or a little before the soft X-ray enhancement. The $H\alpha$ start times used were the earliest reported among the reports from several different observatories. The idea was that the earliest report probably corresponded to the observatory having the clearest observing conditions; but perhaps some of these early reports were the result of a data processor's bias toward picking the earliest starting time rather than of excellent seeing conditions. When an average start time is used for the reports of the various $H\alpha$ observatories, the distribution is shifted so that the start of the soft X-rays is at about the same time or a little before the start of the $H\alpha$ flare on the average. Since the percentage increase in $H\alpha$ radiation from the whole sun is very small during a flare, $H\alpha$ observations are not well suited for automatic detection of solar flares. Even if the spatial field of view were effectively decreased (for example with a raster scan technique) in order to increase the percentage $H\alpha$ enhancement, it would still be difficult to achieve the percentage increase observed at X-ray wavelengths.

2.7 Comparison of Soft X-Ray Enhancements and Extreme Ultraviolet Flashes

Thirteen EUV flares observed by Drs. L.A. Hall and H.E. Hinteregger of AFCRL with a spectrometer aboard OSO-3 were studied. My general conclusion was that the EUV flashes were much like the centimeter radio and hard X-ray observations. The EUV flashes tended to have faster rise times and peak earlier than the soft X-rays, but the EUV start time lagged behind the soft X-ray start time, in seven out or eight cases for which X-ray data were also available. For 10 out of 13 cases, the reported start time of the centimeter-wavelength radio burst occurred before or at the same time as the start of the EUV flash. Since the percentage radiation enhancement for the whole sun seems to be smaller at EUV wavelengths than at centimeter wavelengths, solar radio measurements would probably be superior to EUV measurements for automatic flare detection, unless the EUV measurements used a raster scan of the sun. In conclusion, there are few data available as yet on the EUV emission of solar flares and those that are available do not indicate that EUV measurements would improve the early detection of solar flares.

One type of sudden ionospheric disturbance called sudden frequency deviations is partly due to flashes of EUV radiation (Donnelly, 1967). Davies and Donnelly (1966) found that on the average, the start of the SFD preceded the onset of the explosive phase of the Hα flare by about 1.5 min. The explosive-phase data used in this study had been processed visually at Lockheed Observatory.

Recently, Angle (1968) of Lockheed Observatory reprocessed their explosive-phase data using a "densichron" to measure the Hα flux variations as a function of time. She found that the start of the rapid-rise phase determined from the densichron measurements preceded the visual estimates on the average by about 1 to 1.5 min. This means that the start of SFD's is about the same as the start of the rapid rise of the Hα flare if the Hα data are processed photoelectrically. Since the Lockheed observers who did the visual processing of their flare patrol films are about the best in the world, this also suggests that our eyes may deceive us more than was generally realized. Comparing the start time of SFD's with the start time reported for OSO-3 8-16 Å X-ray events, I found that the X-rays started 3.5 min before the SFD's on the average. Hence, the indirect evidence of EUV flashes obtained from SFD's does not indicate that EUV measurements would improve the early detection of solar flares.

2.8 Comparison of Soft X-Rays and Hard X-Rays

Hard X-ray enhancements ($\lambda \ll 1$ Å) tend to have faster rise times and peak earlier than soft X-ray enhancements ($\lambda \geq 2$ Å), much like the centimeter-wavelength burst. The VELA data (Conner et al., 1964) indicate that hard X-ray measurements are not as good as soft X-ray measurements for the early detection of flares because the X-ray emission for some flares does not extend down to the hard X-ray wavelengths. Conversely, there is no definite evidence that hard X-ray flares occur without being accompanied by a soft X-ray enhancement. DeJager (1967) has reported on one hard X-ray flare when no D-region SID's were reported, although an SFD was observed over Africa. This hard X-ray flare was rather impulsive and if the soft X-ray enhancement were similarly impulsive the D-region SID effects may have been too small and too short in duration to distinguish from the noise normally present in these SID data. The OGO I and III hard X-ray data (Arnoldy et al., 1968 a and b) compared with Explorer 33 (2-12 Å) data do not indicate that the start time of hard X-rays is any earlier than that for soft X-rays. In conclusion, no evidence that hard X-ray measurements would improve the early detection of solar flares was found. Hard X-ray measurements would be important if the goal were to detect solar flares having energetic nonthermal processes rather than just detecting any solar flare of Hα importance 1 or greater. Arnoldy et al. (1968a) found that hard X-ray bursts preceded large electron events for flares located west of the central meridian; hence, hard X-ray measurements provide a warning of electron events. It is too bad that they do not provide a warning of the more dangerous proton events.

3. FLARE ALARM SIMULATION

Explorer 30 data were studied using a computer program to simulate the planned soft X-ray (1 - 8 Å) ATM alarm system to try to learn how much delay after the "after-the-fact" start time there was before the alarm detected the flare. These data were provided through the courtesy of Mr. R.W. Kreplin of NRL and R.H. Olson of ESSA. The advantages of the Explorer 30 data are as follows: (1) very high time resolution; for some events a measurement of the sun was made every 0.83 sec; (2) high intensity resolution; (3) good calibration; (4) low instrument noise; and and (5) several different wavelength ranges, 0.5-3, 1-8, 8-16, and 44-60 Å. The disadvantages are: (1) small dynamic range, (2) linear rather than logarithmic recording of the data, and (3) short periods of observation, about 15 to 20 min as the satellite passed over the telemetry ground station. Because of the short period of observations, the beginning was missed for most of the flares observed by Explorer 30. Because of the low dynamic range, the detectors were often saturated, especially during a flare and sometimes even before the flare started. As a result, very few of the Explorer 30 observations were suitable for this study. Table 2 lists the flare events studied in detail. Table 3

TABLE 2. Explorer 30-X-Ray Flares used in Simulated Flare Alarm Studies

Date	Hα Flare Observatory	Hα Flare Importance	Hα Start Time UT	Wavelength Range of X-Ray Detector (Å)	Observation Period (Hours, Minutes) Start Time	Observation Period (Hours, Minutes) End Time	Aspect Angle (Degrees)	Particle Interference	Δt Time Between Adjacent Data Samples (Seconds)	Comments
March 15, 1966	Lockheed	SN	2237	44-60	2233	2247	-2.75	No	2.56	
	Hale	1N	2241	8-16	2233	2243	-2.75	No	2.56	
March 24, 1966	Lockheed	SN	1955E	44-60	1950	2005	-2.75	No	2.70	
March 28, 1966	Hale	SB	1805	44-60	1751	1807	+5.25	No	2.775	
	McMath	SF	1806	8-16	1751	1807	+5.25	No	2.775	
April 11, 1966	Sac Peak	1N	1430	1-8	1425	1440	-2.75	No	3.08	
	McMath	SN	1435	8-16	1425	1440	-2.75	No	3.08	
April 24, 1966	Huancayo	SN	1409	44-60	1408	1411	-3.25	No	3.38	
	Graz	1B	1410	8-16	1408	1416	-3.25	No	3.38	
	Ondrejov	1N	1411E							
May 24, 1966	Huancayo	SF	1807	44-60	1743	1757	-3.25	No	~4.7	
				8-16	1743	1757	-3.25	No	~4.7	
May 25, 1966	Sac Peak	1B	1530	44-60	1559	1613	-3.25	No	~4.7	Aspect angle changes from 3.25° to -2.75° during pass, ∴ aspect angle $\approx -3.0^{\circ}$
	Huancayo	1B	1530	8-16	1559	1605	-2.75	No	~4.7	
July 24, 1966	Hale	SN	0151	8-16	0149	0201	-5.25	No	7.65	
August 31, 1966	Lockheed	2B	1840	1-8	1844	1852	+3.25	No	15.5	Minor telemetry interference
	McMath	1N	1853	8-16	1843	1852	+3.25	No	15.5	
Sept. 18, 1966	Meudon	1B	1452	44-60	1446	1456	-26.5	Very Small	0.83	
	McMath	1B	1452	8-16	1446	1500	-26.5	Yes*	0.83	*Strong particle interference from 1448-1454 UT
	Anacapri	1B	1454E							
Dec. 9, 1966	Lockheed	2B	1755	1-8	1752	1758	+2.75	No	1.30	
	Sac Peak	2B	1759E	8-16	1752	1758	+2.75	No	1.30	
April 14, 1967	Hale	2B	1700	8-16	1659	1708	+2.75	No	2.67	
	Sac Peak	2N	1706							
May 19, 1967	Sac Peak	SN	1503	1-8	1455	1507	-1.25*	Slight	3.3	*Aspect angle hard to read
	McMath	SB	1503	8-16	1455	1507	-1.25	No	3.3	

TABLE 3. Nonflare Explorer 30 X-Ray Measurements

Date	Wavelength Range of X-Ray Detector (Å)	Observation Period Start Time (Hours, Minutes, Seconds) (UT)	Observation Period End Time (Hours, Minutes, Seconds) (UT)	Aspect Angle (Degrees)	Particle Interference	Δt Time between adjacent data samples (Seconds)	Comments
Aug. 1, 1966	44-60	230303.15	231114.7	+5.25	None to very small	8.60	Some telemetry interference
	8-16	230310.02	231120.9	+5.25		8.60	
Aug. 10, 1966	44-60	220242.80	221209.5	-5.25	No	9.90	Some telemetry interference
	8-16	220249.90	221157.1	-5.25	No	9.90	
Nov. 3, 1966	44-60	182824.27	183214.6	-2.75	No	1.07	
	8-16	182824.01	183214.3	-2.75	No	1.07	
Jan. 24, 1967	8-16	195118.70	195604.6	-2.75	No	1.68	
Apr. 14, 1967	8-16	183427.07	184011.6	+2.75	No	2.70	
May 30, 1967	8-16	125428.10	160138.4	-0.75	Very small	3.70	Small telemetry interference.

lists some Explorer 30 data which were studied to provide information on how variable the X-ray measurements were when no flares occurred.

The available information on the planned ATM flare alarm system was as follows: (1) the only radiation measurements would be in about the 1-8 Å range (Dr. L. Van Speybroeck, American Science and Engineering, private communication), (2) the alarm would be set off if the soft X-ray flux exceeded a threshold level set by an astronaut, and (3) five threshold levels spaced so that each level was four times the flux rate of the next lower level would be available (ATM EXPT S054, 1967, p 6-21). (According to a recent communication from Dr. L. Van Speybroeck of American Science and Engineering, the threshold level spacing has been revised from 4 times to about 1.45 times.) The time variations of the Explorer 30 1-8 Å and 8-16 Å observations should be similar to what a 5-20 Å detector would observe. In the computer simulation studies, the flux rate for the lowest threshold level was made arbitrarily; only the spacing between threshold levels was really important for the simulation study. Calculations were first made for one base threshold level and then for a second base level equal to twice the first value.

The results of this simulation study indicated that the four-times spacing of threshold levels was too coarse because it resulted in the detected start time being too much later than the actual start of the X-ray enhancement and solar radio burst. The study indicated that twice as many threshold levels did not provide a substantial improvement. (The revised spacing of 1.45 times looks good but has not yet been studied in detail.) Further study of actual X-ray and solar radio data should be made to determine the optimum spacing of threshold levels.

Figure 17 shows the start of a fairly large soft X-ray and solar radio burst. The small jiggles in the soft X-ray points are largely due to scaling and plotting errors. The X-ray flux increases slowly from 1753 to 1756 UT, then increases at an increasing rate. The 1-8 Å data seem to be better than the 8-16 Å since their percentage increase is much greater than for the 8-16 Å data. The start times reported

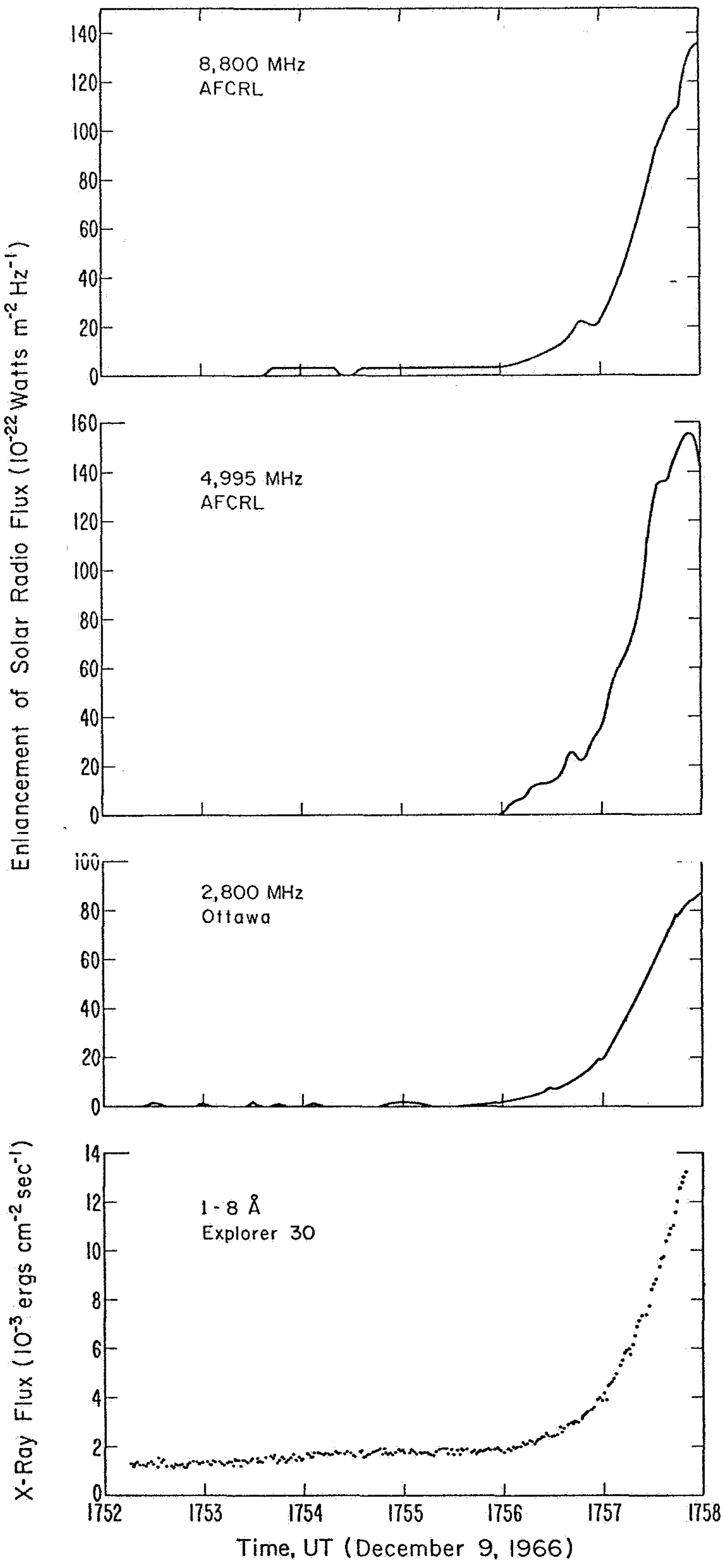


Figure 17. Start of the X-ray and solar radio burst for the solar flare of 1756 UT December 9, 1966.

in SGD for the radio burst at 10,700 MHz (1757.1 UT), 960 MHz (1759.4 UT), and 486 MHz (1800 UT) lag significantly behind the X-ray start time. Although the after-the-fact start time reported for 1415 MHz and 606 MHz was 1756 UT, the radio enhancement at these frequencies would not have been detected by a real-time alarm system until several minutes later. The 2800, 4995, and 8800 MHz data in figure 17 are as good as the 1-8 Å data for detecting the early start of this flare if the increase in X-rays from 1753 to 1756 UT is too slow or small to be certain that a large flare would follow. Even if the increase in X-rays from 1753 to 1756 UT were too slow to justify starting high resolution flare observations, it might still be useful for triggering an alarm to warn the astronauts that the X-ray flux is increasing. An X-ray alarm using a four-times spacing might not detect this flare until 1757.2 UT for 1-8 Å or until about 1800.7 UT for the 8-16 Å data. This latter time would miss much of the rapid-rise part of the flare.

Basu and Covington (1968) found that the initial growth of 2800 MHz bursts has a time dependence given approximately by $\Phi = ct^2$. The start of the X-ray enhancement as well as the radio bursts in figure 17 exhibit this time dependence. Indeed, the start of each of the X-ray events in table 2 has nearly a t^2 time dependence.

The 1b flare of September 18, 1966, is an example where the start time detected by the simulated alarm system lagged several minutes behind the start-time of the solar-radio bursts. In addition to the problems of the coarse spacing of threshold levels, there was a problem in that the X-ray flux was decreasing before the flare. Consequently, the threshold level that rose just above the flux level shortly before the flare was not used to trigger the flare alarm. Several other events also showed a preflare slow decay followed by a slow rise. This shows that slow changes in flux level should be monitored and that the flare alarm level may need to be reset, sometimes as often as every 5 min.

The "after-the-fact" X-ray start times for the events listed in table 2 occurred at about the same time or slightly earlier than the reported start times for the radio bursts, in agreement with the results in figures 14 and 15. The X-ray measurements seemed to be a little better than the solar radio data at indicating a gradual rise just before the main burst. For practical purposes, if the alarm has to be triggered by the main rise rather than by the earlier slow rise, then the 2695 MHz, 2800 MHz, and 4995 MHz data are about as good to use as the soft X-rays. The X-ray measurements indicate that 1-8 Å is as good or better than the 8-16 Å range and that both of these are better than the 44-60 Å range for the automatic early detection of a flare.

The interference in soft X-ray measurements from particles colliding with the satellite was a minor problem for the data in table 2. Such interference would be a non-neglible problem for a flare alarm system using only X-ray measurements. Detectors sensitive to the particles but insensitive to the solar X-rays should be incorporated into the X-ray alarms svstem to avoid false alarms. Such a system would still suffer from reduced sensitivity in particle anomalies. This problem might be alleviated by also making centimeter-wavelength radio measurements with equipment having a sensitivity comparable to present ground-based solar radio receivers. (The 297 MHz and 2000 MHz ATM communications receivers appear to be a little too insensitive to do a good job of detecting the start of the flare.) The qualification "might" was included here because although the colliding particles might not cause much radio noise directly, indirect effects unknown to this author might severely reduce the value of radio measurements when the satellite is passing through a particle anomaly. This matter should be studied further. There probably exist satellite communications or telemetry data which could provide a definite answer to this.

4. DISCUSSION

4.1 Conclusions on Radiation Measurements for a Flare Alarm

The conclusions of this study pertinent to the early automatic detection of solar flares of Hα importance greater than or equal 1 are as follows:

1. Soft X-ray measurements are potentially about the best measurements for an alarm system for the early detection of solar flares. Although hard X-rays, centimeter-wavelength solar-radio bursts, and flashes at certain EUV wavelengths usually have faster rise times and peak earlier than the soft X-rays, the data available to date show that on the average the measurable start time of the soft X-rays occurs earlier than the start times for these other types of data. The best wavelength range to use is not clear, but it appears that data taken in the 1-8, 2-12, or 8-16 Å range are better than 44-60 Å or $\lambda < 1$ Å. Although the "after-the-fact" start time will generally precede the start time detected by a real-time alarm system, the data studied in section 3 indicate that the alarm-detected start time can be as early or earlier for soft X-rays than for solar radio bursts, providing the alarm system is sensitive enough.
2. The X-ray alarm system discussed in ATM Exp S054 (1967) with a four-times spacing between threshold levels is too coarse to assure the early detection of flares. (The revised spacing of 1.45 times should be much better.)
3. If the X-ray alarm is made more sensitive, the problem of false alarms due to particle interference and subflares will increase. The percentage of X-ray enhancements that are accompanied by flares of Hα importance greater than or equal to 1 is roughly inversely

proportional to the smallest X-ray enhancement that can be detected by the alarm system. Figures 7 and 8 indicate that a simple threshold device could not avoid false alarms from subflares if the threshold levels were spaced closer than four times or 0.001 ergs cm^{-2} sec^{-1} in the 8-16 Å range. An alarm system that also takes into account the rate of change of the flux should be used.

4. Available information on extreme ultraviolet (EUV) radiation does not indicate that EUV measurements would improve the alarm system. More EUV measurements should be made and the preflare characteristics of these data should be studied in detail. The available data indicate that EUV enhancements have characteristics ranging from being similar to the impulsive centimeter radio bursts to resembling the slower soft X-ray bursts, depending on the wavelength observed. The percent flare enhancement of EUV radiation is much less than for soft X rays.

5. Hard X-ray measurements would not improve an alarm system intended to detect all flares of Hα importance 1 or greater, but would be valuable for predicting electron events.

6. Solar radio measurements would not provide a remarkable improvement over a soft X-ray alarm system operated at its full potential, but it could provide about as good an alarm as the soft X-ray measurements. The available data suggest that measurements in the 2,000 to 5,000 MHz range would be best from the viewpoint of early detection and for complete detection. The addition of centimeter radio measurements to an X-ray alarm system should provide the following improvements: (a) confirmation of a flare, thereby providing more certainty against false alarms; (b) redundancy, in case of malfunction of the X-ray alarm system; (c) an alarm less

influenced by particle interference; (d) an earlier detection of the start time for at least about 10 percent of the Hα flares of importance 1 or greater; and (e) an increase perhaps of about 10 percent in the number of flares detected. (This last value of 10 percent assumes the X-ray alarm system can detect increases in the 5-20 Å radiation of 0.002 ergs cm^{-2} sec^{-1} and for a radio alarm system as sensitive as present ground-based systems. For the less sensitive X-ray alarm being planned, this value would be higher; and, conversely, for a radio alarm system with less sensitivity, the value would be lower.)

4.2 Suggestions for Further Study

There presently exists a wealth of high quality recordings of soft X-ray and solar radio data for flares which were not available in time for the present study. These data should be used in flare alarm simulation studies to evaluate and improve flare alarm designs. Problems due to particle interference and the use of solar radio measurements to alleviate these problems should be studied further. The use of an alarm sensitive to the time rate of change of flux as well as the flux intensity should be studied. Such a system might permit an increase in sensitivity for the early detection of flares without increasing the false alarm rate.

4.3 Suggestions of Possible Interest to the ATM Program

The original purpose of the ASE X-ray alarm system seems to have been to automatically start the flare mode of the ASE X-ray experiment on ATM. Apparently, the only reason for the alarm and display for the astronaut was to notify him that the flare had started so that he could center the X-ray telescope on the X-ray flare. The use of this alarm has seemingly been extended to function as a start switch for the flare mode of several of the ATM experiments. If the flare alarm is made more sensitive in order to detect the start of the flare then the number of false alarms will undoubtedly increase. Since the available film for flare observations varies from experiment to experiment, the number of false alarms that can be afforded varies among the experiments. Hence, different experiments need different threshold levels in the flare alarm system.

When the flare predictions are very high, or if most of the ATM mission has been completed and no flare observations have been made, it would probably be desirable to lower the threshold level used to trigger a given experiment. Also, it might be desirable to let the astronaut set an alarm for himself that is more sensitive than the threshold level being used to trigger the flare mode of the experiments in operation at the time. It might be helpful to provide the astronaut with a chart record of the X-ray flux over the past two orbits. This would quickly and simply allow him to put current X-ray flux measurements in perspective rather than having to rely on his memory of the Exposure Display Counter or Intensity Display Counter.

It might be of value to make the rate at which data are taken to be proportional to both the rate of change and the increase of the soft X-ray flux and/or solar radio emission, rather than having just a high-time resolution mode and a low time resolution mode. This could reduce the problem of early detection versus false alarms from subflares and it might conserve the data film. When the soft X-ray flux starts to increase slowly, it is hard to tell whether a large flare will follow or just a subflare; but if the flare is large, it would probably be nice to have data for the early gradual rise portion at a higher rate than the nonflare rate. Since the rise is gradual a very high rate would probably not be needed; and since the flare could turn out to be small, the high rate could waste much film. It should be possible to solve this problem with a data rate controlled by a combination of the time rate-of-change and amount of increase of the X-ray flux. Such a system could provide very high rates during the rapid onset of the flare, moderate rates at the peak of the radiation, and slow rates during the slow decay.

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